EVOLUTION OF MAGNETIZED, ROTATING, ISOTHERMAL CLOUDS

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1. Introduction

Molecular cloud cores, in which star formation process now proceeds, are often found with elongated shape. This suggests that the core collapsed preferentially along the direction parallel to the global magnetic field and/or parallel to the cloud's initial angular momentum. Actually the magnetic field strength in the cloud has been measured recently with the Zeeman splitting (Goodman *et al.* 1989). The authors indicate the magnetic field of 10 – 30 μG exists in the cloud. Further, the observation of polarization in the near IR from background stars shows that the magnetic field runs perpendicularly to the major axis of the cloud (Tamura *et al.* 1987). As for the angular momentum, the rotation rate of 0.2 – 6 km s^{-1} pc^{-1} is reported (Goldsmith and Arquilla 1985) in 16 dark cloud regions. If the cloud collapses from the diffuse cloud with density $n \sim 1\mathrm{cm}^{-3}$ with strictly conserving the angular momentum which was shared from the galactic rotation, the rotation rate of the cloud will be $\Omega_{J=\mathrm{const}} \sim 3(n/1000\mathrm{cm}^{-3})^{2/3}\mathrm{km\ s}^{-1}\mathrm{pc}^{-1}$ (Mouschovias 1987). ~~In a present paper, I will study~~ the evolution of the rotating magnetized cloud.

2. Equilibrium Solutions and Critical Mass

First, I will see the equilibrium structure in which the self-gravity is couterbalanced by thermal pressure, magnetic force, and centrifugal force. This will enable us to estimate the critical mass of the cloud M_{cr}, which divides the clouds into subcritical clouds $M < M_{\mathrm{cr}}$ and supercritical clouds $M > M_{\mathrm{cr}}$.

The equilibrium solution is characterized by four parameters: the mass M_{cl} (or the central density ρ_{c}), plasma beta of the ambient medium $\beta_0 \equiv p_{\mathrm{ext}}/(B_0^2/8\pi)$, magnetic flux threading the cloud $\Phi_B \equiv \pi R_{\mathrm{cl}}^2 B_0$, and specific angular momentum $j \equiv 2/5 R_{\mathrm{cl}}^2 \Omega_{\mathrm{cl}}$. Numerical method is described in other paper (Tomisaka *et al.* 1988*a*). Figure 1 represents the M_{cl} vs. ρ_{c} relation for fixed R_{cl}. This shows that the maximum mass, which is shown by tick mark, increases according to the increase of magnetic field (decrease of β_0). Angular momentum has a similar effect: with increase of j, the critical mass increases for fixed β_0. From these, I obtained an approximate formula for the critical mass of the cloud with *both* magnetic field and rotation as

$$M_{\mathrm{cr}} \simeq \left\{ M_{\mathrm{mag}}^2 + \left(\frac{4.8 c_{\mathrm{s}} j}{G}\right)^2 \right\}^{1/2} \tag{1}$$

M_{mag} means the critical mass of the nonrotating cloud as

$$M_{\mathrm{mag}} \simeq 62 \left\{ 1 - \left[\frac{0.17}{G^{1/2}|dm/d\Phi_B|_{\mathrm{c}}}\right]^2 \right\}^{-3/2} \frac{c_{\mathrm{s}}^4}{p_{\mathrm{ext}}^{1/2}(4\pi G)^{3/2}}, \tag{2}$$

where $G^{1/2}|dm/d\Phi_B|_{\mathrm{c}}$ and c_{s} represent the mass-to-magnetic flux ratio at the center and isothermal sound speed (see Tomisaka *et al.* 1988*b* and 1989).

3. Quasistatic Evolution Driven by Plasma Drift and Magnetic Braking

Here, the evolution of *subcritical* cloud is studied, because the supercritical cloud will collapse in a short dynamical time scale. Subcritical clouds evolve driven by the plasma drift (ambipolar diffusion) and magnetic braking. Since the evolution time scales driven these two processes are ordinarily much longer than the dynamical time scale of the cloud (free-fall time at the center), the cloud evolves in a quasi-static fashion. Due to the plasma drift, mass and angular momentum is transferred across the magnetic field inwardly. As for the magnetic braking, because the torsional Alfvén wave propagating in the ambient medium (ρ_a) transfers the angular momentum, angular momentum flux flowing through a flux tube is estimated as $\sim 2V_A\rho_a R v_\phi \times$ (area of the magnetic tube).

Figure 2 shows the evolution of a model cloud. (a) corresponds to the initial state ($t = 0$). The cloud rotates almost rigidly. At $t = 2\times10^6$ yr (b) the central density increases from $n_c = 1.6\times10^4\mathrm{cm}^{-3}$ ($t = 0$) to $n_c = 3.3\times10^4\mathrm{cm}^{-3}$ due to the increase of the mass-to-flux ratio by the plasma drift. Beyond $t = 4.3\times10^6$ yr (c), no quasistatic solutions exist and this indicates that the cloud enters the dynamical contraction phase after that. About 80 % of the initial angular momentum is lost in $t = 4.3 \times 10^6$ yr. While the central density increases by a factor 100 during the quasistatic evolution, the mass-to-flux ratio at the center increases only by a factor 2.

The time scales of the plasma drift and angular momentum loss are expressed, respectively, as $\tau_P \simeq 15(G\rho_c)^{-1/2} \sim 3 \times 10^6\mathrm{yr}(n_c/10^5\mathrm{cm}^{-3})^{-1/2}$ (Mouschovias 1987) and $\tau_{||} \simeq 2.4 \times 10^6\mathrm{yr}$ $(M_{\mathrm{cl}}/10.7M_\odot)(R_{\mathrm{cl}}/0.26\mathrm{pc})^{-2}$ $(B_0/30\mu G)^{-1}(\rho_a/3.8 \times 10^{-23}\mathrm{cm}^{-3})^{-1/2}$ (Shu *et al.* 1987). The evolution is determined by these two time scales *and* available time left to the cloud (or how close the mass of the cloud is to the critical mass).

(1) the cloud mainly supported magnetic field. (a) the cloud with mass much less than the critical mass (Fig. 2): the cloud is long lived $\sim (4-7)\times 10^6$yr and loses almost all the angular momentum (80%) in the quasistatic evolution phase. (b) the cloud with mass close to the critical mass: since the plasma drift works effectively in such a cloud, the cloud enters the dynamical contraction phase fast ($\sim 10^6$yr). A fairly large part of the angular momentum (60%) remains in the cloud at the final phase of the quasistatic evolution.

(2) the cloud in which rotation also plays an important role: since the decrease of angular momentum reduces the critical mass, magnetic braking makes the quasistatic evolution end in $\sim 6 \times 10^6$yr. In either cases (1) or (2), clouds enter the dynamical contraction phase in several 10^6yr.

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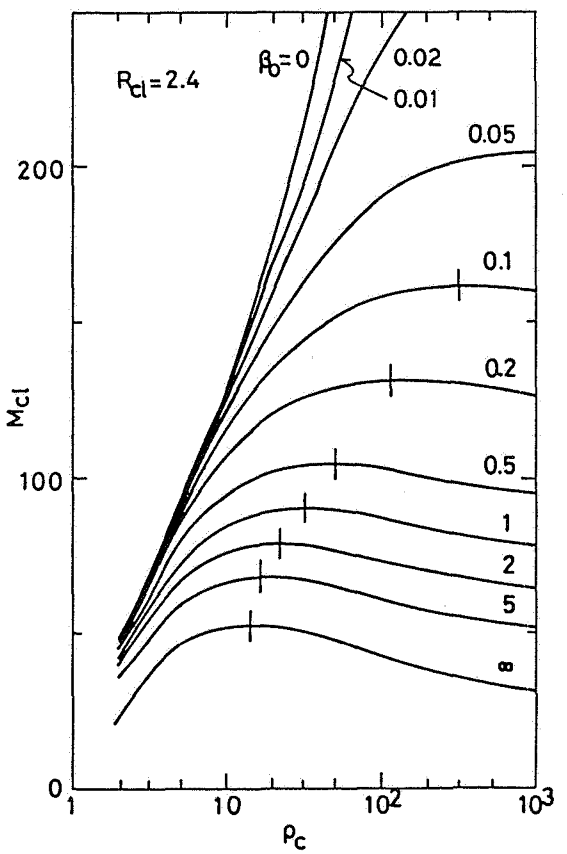

FIG 1—Mass of the cloud, M_{cl}, vs. central density, ρ_c, for various values of β_0. Except for $\beta_0 = 0$, M_{cl} takes a maximum value, which increases with increasing strength of the magnetic field B_0. The critical density, at which the mass reaches the maximum, also increases with increasing strength of the magnetic field.

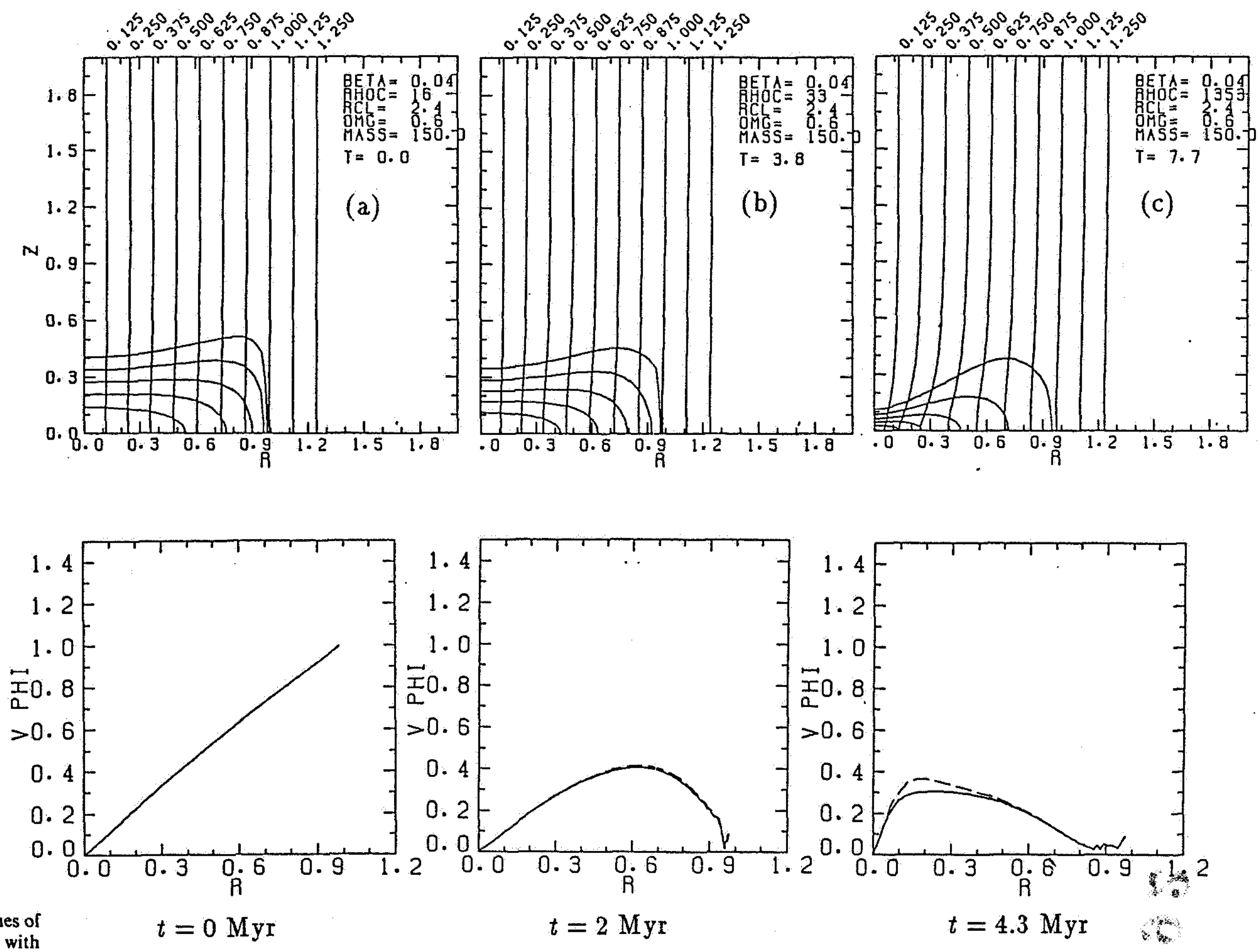

FIG 2.—— The evolution of magnetized rotating clouds with $T = 10\mathrm{K}$, $M_{cl} = 10.7 M_\odot$, $B_0 = 30\mu\mathrm{G}$, $\Omega_{cl} = 1\mathrm{km\ s^{-1}\ pc^{-1}}$, $R_{cl} = 0.26\mathrm{pc}$, $p_{ext}/k = 10^4\mathrm{K\ cm^{-3}}$ and $\rho_a = 10\mathrm{cm^{-3}}$ at (*a*) $t = 0$, (*b*) $t = 2 \times 10^6$ yr, and (*c*) $t = 4.3 \times 10^6$ yr. In the upper panel, the magnetic field line, which runs almost vertically, and the density contour are plotted. The contour level of the density is taken as $\log \rho = [(\log \rho_c)/5]n$, for $n = 0 - 4$. The horizontal and vertical axis mean, respectively, the normalized distance as r/R_{cl} and z/R_{cl}. In the lower panel, the normalized rotation velocity $v_\phi/(R_{cl}\Omega_{cl})$ is plotted against the normalized radial distance r/R_{cl}.